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## ABSTRACT

Beginning college physics students' misconceptions about moving objects, their mathematics skills, and formal reasoning ability, are all believed to be related to their achievement in physics. It is hypothesized that students whose knowledge structures include misconceptions that are in conflict with concepts in the lectures and text will have difficulty in learning classical mechanics. Multiple regression analysis of scores on tests of mathematics skills and formal reasoning ability confirmed that no linear relationship exists between these independent variables and scores on a classical mechanics exam. However, an index of misconceptions about moving objects accounts for greater variance in classical mechanics exam scores. (Author)

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FACTORS INFLUENCING LEARNING  
OF  
CLASSICAL MECHANICS

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## Introduction

During the past decade much attention in the physics education community has been turned to the problems surrounding the learning and teaching of introductory physics for the non-physics major. Within the domain of introductory physics, the teaching of classical mechanics is a focus of special concern. It is generally agreed that mechanics, often the first subject treated in introductory courses, is especially troublesome for many students.

Educators cite various reasons for this apparent opacity of physics, and especially mechanics, to many students, and have suggested and attempted various resolutions of the difficulty. Many variables that may contribute to students' success in learning physics have been explored, at least tentatively. Foremost among these are (1) mathematical skills, (2) general level of cognitive development, (3) specific cognitive processes, and (4) content preconceptions. Measures of student success in physics reported in the literature also are diverse. Final grades, scores on specially designed tests of content knowledge, ability to solve certain problems, and even the attainment of "formal" cognitive operations all have been used as output measures. It is apparent from even so brief a listing as this that, if one hopes to sort out those factors that influence students' successful learning of introductory physics, careful analysis of both input measures, instruction, and output variables, and systematic analysis of the interactions between variables are required.

Consider, for example, the input variable, mathematical skills. For many in the physics community, the assumption that proficiency in mathematics provides the necessary and, perhaps, sufficient condition

for success in learning physics has guided practice for quite a few years. Some recent studies have attempted to assess how firm the grounds for this belief are. As part of a larger project to determine factors that correlate with success in learning physics, Cohen, Hillman and Agne (1978) found, not surprisingly, that SAT mathematics scores correlate highly both with the level of the physics course (they included four courses, from a survey course to one requiring calculus) and with final grades in the course. These authors admit that "final course grade may not be the best measure of actual achievement in physics" and they plan to use standardized achievement tests in a future study. But what is missing in both final course grades and standardized tests is that the outcome measure is not adequately specified in terms of the cognitive requirements of the physics courses. It is also typical in such studies to find only a mere mention of the textbook used and the bare information that a course was taught "in the traditional way."

Hudson and McIntire (1977) attempted a more refined analysis of the algebraic and trigonometric "tools" presumably needed in a non-calculus physics course. These tools were: (1) linear algebraic equations in one unknown, (2) parametric equations in two unknowns, both linear, (3) parametric equations in two unknowns, one a quadratic, (4) graphical analysis, (5) quadratic formula, (6) Pythagorean theorem, (7)-(9) definitions of sine, cosine, and tangent. On the basis of this analysis they prepared a diagnostic instrument which was administered prior to the beginning of instruction, and compared scores on the pretest with final course grades. They report that the test was a better predictor of a probability of failure than of "success," and they conclude that

"mathematical skill is only one of the several factors necessary to physics, and a high score on the mathematics test is no guarantee of success in physics." Although their conclusion is probably correct with respect to the importance of mathematical skills, we are still left with a number of questions: Are the nine prerequisite skills they identified adequate and complete? Are they actually required in the course? We have no way of judging these matters from the authors' descriptions. To what extent was proficiency with these skills related to the final grades?

The traditionally held belief that there is an important relationship between mathematical skills and physics success has been supplemented by some educators who view as appropriate the application of recent developments in cognitive psychology to the concerns of the physics instructor. These investigators have approached the problem in various ways. Some have drawn upon the work of Piaget and his theory of cognitive development. Others have taken up an information processing psychology perspective and have attempted to analyze and specify the cognitive skills required to solve certain physics problems. Still others have attended to the conceptions about physics that students bring to their study of physics courses.

Judging from the volume of reports dealing with the subject, a particularly attractive idea to many has been the notion, derived from Piaget's work and supporters of his cognitive developmental framework, that a prerequisite for success in the learning of physics is the attainment by the individual of "formal" modes of reasoning. "Formal" cognitive operations can be variously defined in either technical or

general terms. The literature dealing with post-secondary physics education usually provides non-technical specifications of components of formal reasoning, such as the following list supplied by Arons (1976): "the capacity to do elementary syllogistic reasoning involving inclusion, exclusion, and serial ordering; discriminate between observations and inferences; recognize incompleteness of information in a line of reasoning; do inductive reasoning in the development of a scientific model and deductive reasoning in predicting consequences of the model; engage in hypothetico - deductive reasoning; do arithmetical reasoning, particularly involving the consequences of division of one number by another."

More technical definitions (see Piaget & Inhelder, 1969) include a description of what Piaget calls (1) the combinatorial system and (2) the INRC group. The meaning of Piaget's elaboration of formal operations, it should be noted, has itself been the object of serious critiques (see, for example, Ennis, 1975). This is an important consideration for two reasons. First, some researchers have tried to validate paper-and-pencil measures of formal operations by arguing that these tasks probe for the operations elaborated in Piaget's theory (for example, Phillips, 1977). Second, many investigators rely upon the tasks developed by Piaget and his co-workers, tasks which are administered in a clinical interview fashion (see Chiapetta, 1976), and it is the relationship of these tasks to the "formal operations" that has been criticized.

Not only are there various definitions of formal operations and various probes into formal thought; there are also studies that explore

the relationships of cognitive level to success in introductory physics. These fall into three broad categories: (1) those (which will not be reviewed here) that assume that physics courses must be modified to accomodate those students not exhibiting formal operational thought (Arons, 1976); (2) those that retain a "traditonal" mode of physics course and try to correlate cognitive level of development with success in the course; (3) those that have compared success between courses taught "traditionally" and those modified for pre-formal students. In all three groups there is a common agreement in the observation that, regardless of which assessment methods are used (paper-and-pencil tasks or clinical interviews), from one-third to one-half of the students taking introductory physics are operating below the normal level.

No studies have been conducted to date that challenge the assumption of educators in group 1 (see above) that traditional courses must be modified. Cohen, Hillman, and Agne (1978), whom we have mentioned earlier, studied the correlation between cognitive level of development and final grade in a range of physics courses. Clinical interviews were conducted to establish cognitive levels. Their data led them to conclude that there is "little correlation between Piagetian level and success in physics courses." Barnes (1977), studying six lower-division physics courses, correlated results from a paper-and-pencil test with final course grades and found that the two were weakly correlated. In both of these studies, the weaknesses of "final grade" as an output measure are evident, and in neither are we provided with an analysis of the physics courses.

In addition to those educators who draw upon the Piagetian



framework, a few have looked for new ideas to another area of cognitive psychology, specifically to the information processing approach. A key feature of this perspective is a focus on the specification of the knowledge and cognitive operations required for the solution of physics problems. Also, in this perspective it is assumed that knowledge is stored in memory as knowledge structures and that success in solving problems is related to the "richness" of these structures and to the ability of the individual to "access" them. For example, Reif, Larkin and Brackett (1976) have analyzed the skills required to understand a relation, definition or law in physics and some of the tasks (strategies) needed to solve a physics problem. They have attempted to teach these skills to students and have concluded, tentatively, that it is possible to teach these skills and, also, that students so taught are more successful problem solvers than those who were not taught. Notice that in this line of research the output measure is clearly specified and is expressed in terms (problem solving) that most physicists would feel comfortable with. Still to be determined, however, are how the expected range of incoming students' abilities in problem solving relates to students' success in physics courses, and how the students' knowledge of the physical world (as opposed to problem-solving skills) influences their performance. It is this last interaction that has caught the attention of a number of investigators.

Clement (1977), Nussbaum and Novak (1976), Leboutet-Barrell (1976), and Waern (1977) have postulated that on the basis of common-sense-world experiences, students often develop understandings of the physical world which are strongly held, and that these conceptions will interfere with the learning of new conceptual relationships during



physics instruction. These conceptions usually are not entirely isolated ideas but, rather, are incorporated in conceptual structures, the whole or large parts of which must be modified during the course of instruction. One goal of research that follows this line, then, is to probe for students' conceptions, as well as to reveal the structures of the conceptions and the modifications in these structures as a result of instruction.

For example, Clement (1977) studied and catalogued the preconceptions of college students in the domain of classical mechanics (specifically, the relation  $\sum \vec{F} = m\vec{a}$ ). He argues that many preconceptions fall into a pattern that may be summarized as a belief that "motion implies force." He concludes that, "The wide diversity of situations shown here in which this system of preconceptions surfaces is indicative of its pervasive nature." This suggests that the system is deep seated and is one source of the difficulties encountered by students in understanding the physical principles associated with the equation  $\sum \vec{F} = m\vec{a}$ .

The empirical studies reviewed strongly implicate mathematical and reasoning skills as important input variables to the learning of classical mechanics. Theoretical papers suggest that conceptions about the motion of objects that students bring to instruction will influence the learning process. However, each of the studies cited describes the influence of a single input variable on an output measure of physics achievement that is not well specified. Hence, little empirical information is now available concerning the combined effects of the input variables of mathematical skills, reasoning skills, and

conceptions about motion on a well-specified output measure for classical mechanics.

The study described in this paper represents an attempt to contribute data about the combined effects of pertinent input variables on student achievement in mechanics. Our purposes are: (1) to describe in some detail the preinstructional knowledge of mechanics, mathematical skills and reasoning skills of a sample of college physics students; (2) to relate these input variables to the students' success in learning classical mechanics; and (3) through an analysis of the instruction the students received, to generate some hypotheses about causal relationships that exist between the input variables and output measure.

## Procedure

### Setting and Sample

This study was conducted during the Fall 1978 Term in the context of an introductory college physics course, Physics 10, a regular 3-credit offering in the College of Arts and Sciences at the University of Pittsburgh. The Physics 10 course begins a two-term non-calculus sequence designed for students who do not major in either physics or engineering. Instruction in Physics 10 is given in three large-group (100-125 students) lectures and one small-group (15 to 25 students) recitation section per week. The course does not include any laboratory sections, and the students themselves do not perform laboratory exercises, but numerous demonstrations are performed in lectures. Apparatus used in the demonstrations is made available in an "open lab," where the students may voluntarily carry out any manipulations they wish. In the 15-week Fall 1978 Term, there were 3 one-hour midterm examinations and a comprehensive 2 1/2 hour final examination. Mechanics was the subject-matter of the Physics 10 course from the beginning of the term through the second hour examination.

The instruction in mechanics was designed with careful deliberation by the course instructor, a full professor who has had many years experience in teaching Physics 10 and other introductory and advanced courses. At the beginning of each major segment of the study of mechanics, the instructor gave the students an outline of the principal

points to be covered in that segment. The subsequent lectures faithfully followed the outline of principal points. In addition to assigned readings in the textbook, Gamow, 1976, the students were expected to complete homework problem sets at the rate of approximately 2 sets every 3 weeks. The students also were given Home Exams, which contained questions similar to those on the hour examinations administered in class. After the students submitted their Home Exams on a specified date, model answers to the questions were posted, and the students were obliged to submit a corrected version of their Home Exams. To assist the students with their homework problems and Home Exam questions on an individual basis, the instructor maintained an extensive schedule of office hours. In some weeks, as many as 10 to 12 hours were devoted to these individual tutoring sessions. In addition, group review sessions for any student who wished to attend were scheduled in the week prior to each of the two hour examinations on mechanics. All in all, not only was the instruction carefully designed, but the instructor also provided various kinds of support to help the students in their study of mechanics.

The students who enroll in the Physics 10 course tend to be quite heterogenous in their backgrounds and major interests. The sample of 110 Physics 10 students included in this study consists of 46 males (42%) and 64 females (58%). The distributions of their years in college (1st year, 2nd year, etc.) and college majors are shown in Table 1. The distributions of the number of years of science studied in high school and the number of years of mathematics studied in high school are shown in Table 2. Physics was not studied in high school by 32 students (29%), while 68 students (62%) reported one year of high school physics

and 4 students (4%) reported two or more years. The distributions of the number of previous credits earned in college science courses and the number of previous credits earned in college mathematics courses are shown in Table 3. None of the information describing the students in the sample shows any remarkable trends, but their diversity is noteworthy.

## Instruments

A pre-instructional assessment of the students in the Physics 10 course was obtained from the administration of three instruments, viz., the Demonstration, Observation, and Explanation of Motion Test, a Logical Reasoning Test, and a Mathematical Skills Test. The success of the Physics 10 students in mastering classical mechanics was assessed by the first two Hour Examinations and by a portion of the Final Examination. Descriptions of all six instruments follow.

### Demonstration, Observation, and Explanation of Motion Test

The Demonstration, Observation and Explanation of Motion Test, the first part of the pre-instructional assessment, has the purpose of exploring both the students' pre-instructional conceptions of certain aspects of classical mechanics and the modes of reasoning which students apply when confronted with problems in a physics context. In this test, which consists of seven sections, A through G, students are asked to observe the motion of physical objects, in various situations. They are directed to describe their observations, answer questions about the motion of the objects, and then provide explanations for their answers.

The test administrator conducts the demonstrations for the students and the students record their responses in an answer booklet. A copy of the questions included in the answer booklet is provided in Appendix A. Two major pieces of apparatus are used: (1) a wooden, 100-cm high pole with colored markers (see Figure 1a) for sections A, B, and D; and (2) a simple version of the Atwood machine (see Figure 1b) for sections C

through G.

The demonstration performed in each section of the test and the responses which the students are asked to make are described below.

Sections A and B - Free Fall. For both of these sections the students observe and give explanations for the motion of objects in free fall. The test administrator holds objects next to the red marker on the wooden pole (Figure 1a) and then releases them. The students are asked to describe the objects' motion, using the blue and green colored markers on the wooden pole as reference points. Section A deals with the motion of a single object, a chalkboard eraser. (see Appendix A, questions A1 through A6). The students are asked to explain what sets the eraser in motion when it is released (question A1, 2, 3) and to describe their observation of the eraser's speed as it passes the blue and green markers (questions A4, 5, 6). In section B, the students observe, compare and explain the freefall motion of two rectangular prisms of equal volume ( $4.5\text{cm} \times 1.5\text{cm} \times 1.5\text{cm}$ ) but different mass, an aluminum block (mass = 32g) and a lucite block (mass = 13g) (see Appendix A questions B1, 2, 3).

Section C - Atwood Machine (system static). For Section C through G, the Atwood machine, a standard piece of apparatus in the teaching of classical mechanics, is used. The arrangement used here (see Figure 1b) consists of a pulley, a pulley support, a nylon string, a plastic bucket containing sand, and a wooden block. The test administrator can vary the mass of the bucket by adding or removing sand. Prior to demonstrating Section C, the administrator prepares the bucket of sand so that its mass equals the mass of the block. In the



demonstration, the string holding the bucket and block is placed over the pulley with the bucket of sand suspended at a level higher than the block. The students are asked to compare the weights of the bucket and block (questions C1, 2, 3).

Section D - Atwood Machine (system in motion). This section has four parts. Initially the Atwood machine is arranged as in Section C, the bucket of sand and the block having equal mass, the bucket suspended at a level higher than the block.

Part D. I. - Fifteen Grains of Sand (questions D1, 2, 3). The administrator tells the students that he is about to add 15 grains of sand to the bucket (i.e., a small enough mass that the bucket will not be accelerated), and asks the students to report their predictions of what will happen. The administrator then adds the sand, and the students record and explain their observations.

Part D. II. - One Scoop of Sand (questions D4, 5). Continuing with the setup from Part I, the administrator adds 1 scoop of sand to the bucket. The bucket now accelerates downward. The students record any differences they observed between the two instances of adding 15 grains of sand and 1 scoop of sand to the bucket, and they explain the observed differences.

Part D. III. - Speed. (questions D6, 7, 8). The administrator then raises the bucket to the pole's red marker and releases it. The students observe the bucket's descent and record their observations and

explanations for the bucket's speed as it descends.

Part D. IV. - Two Scoops of Sand (questions D9, 10). Another scoop of sand is added to the bucket and (as in Part D. III.) the bucket is raised to the red marker and released. The students observe, compare, and explain the differences in the speeds of the bucket with one and two extra scoops of sand.

Section E - Atwood Machine (different objects of equal mass; constant speed). The administrator removes the two extra scoops of sand and sets the base of the bucket at the same level as the base of the block. The administrator then pushes down slightly on the bucket so that it descends at a constant speed and asks the students to compare the weights of the bucket and block (question E1). The students also respond to four multiple-choice questions concerning the forces acting in this situation (questions E2 through 5).

Section F. - Atwood Machine (cylinders of equal mass; constant speed). In sections F and G, two weighted plastic cylinders of equal mass and joined by a nylon string replace the bucket of sand and the wooden block on the Atwood machine. The test administrator suspends the two cylinders at the same level and then pushes upward on the bottom of one of the cylinders. The students are asked to explain why the cylinder which was not pushed moves downward, and why the cylinders continue in motion after the push stops (questions F1, 2).

Section G - Atwood Machine (transfer of string and cylinders). For this final section, the test administrator removes the two cylinders and string from the pulley of the Atwood machine and transfers them to the

pulley of another machine. In this set-up, the pulley is attached at the end of 45cm-long board which lies horizontally on a table. The pulley extends over the table's edge and its turning axis is parallel to the floor. In this machine, instead of the two cylinders hanging vertically below the pulley as on the Atwood machine, one hangs vertically below the pulley and one rests on the horizontal board.

After transferring the string with the two cylinders to the other machine's pulley, the administrator holds the cylinder at the far end of the board and asks the students to predict what will happen when the cylinder is released. When the students' predictions have been recorded, the cylinder is released, and the students compare their observations with their predictions (questions G1, 2, 3).

#### Logical Reasoning and Mathematical Skills Tests

The pre-instructional assessment also included two additional instruments, which probe the students logical reasoning ability and mathematical skills, respectively. Both of these instruments are administered to the students in test booklets, containing the questions and spaces where students record their answers and their reasoning. Both tests are administered without a time limit.

The Logical Reasoning Test contains 10 questions. The maximum possible score is 10 points. The questions require the student to apply logical reasoning to verbal and diagrammatic representations of physical world situations. Three of the questions refer directly to aspects of physics. Four questions require the use of proportional reasoning

skills, and three are a slightly modified version of the Karplus Islands Puzzle (Karplus & Karplus, 1970), which purportedly tests for aspects of formal reasoning (see Blake, Lawson, & Norland, 1976 for a critique of the Islands Puzzle).

The Mathematical Skills Test contains twelve questions, most with subparts. The maximum possible score is 35 points. The several questions test for the following classes of mathematical skills: (a) conversion of numbers from scientific notation to ordinary notation and from ordinary notation to scientific notation; (b) determination of numerical relationships among line segments and angles in similar and congruent triangles; (c) application of the definitions of sine, cosine, and tangent to do calculations in right triangles; (d) conversion of quantities from one unit to another; (e) proportional analysis of variables from an equation expressing a functional relationship; (f) matching a verbal description of a functional relationship with an equation that formally expresses the relationship; (g) writing equations that express direct and indirect relationships between variables  $x$  and  $y$ ; and (h) analysis of a displacement-time graph.

#### First and Second Hour Examinations and Final Examination

The two hour examinations were designed to assess the students' mastery of classical mechanics, as was a portion of the Final Examination. The First Hour Examination was administered to the students in a lecture period during the fifth week of the course, and the Second Hour Examination was administered in the same way during the ninth week. Two equivalent forms of each Hour Examination were prepared. When

the examination was administered, students seated in alternate seats received the blue form while their neighbors on both sides received the green form. The time allowed for students to complete each of the Hour Examinations was 50 minutes.

Both the First and Second Hour Examinations contain several types of questions and assess the students on several behaviors with respect to the subject matter of classical mechanics. The question types include true-false items, multiple-choice items, and questions where the student supplies short written answers. However, the principal type of question, which accounts for 40% to 50% of the total examination score, presents a quantitative problem in mechanics and requires the student to find a numerical solution. The several questions call upon different behaviors on the part of the students answering them. These student behaviors, classified according to the specifications devised by Klopfer (1971), provide a means for examining the level of understanding assessed by a test instrument. For the First and Second Hour Examinations, the student behaviors with respect to mechanics that are assessed, the number of points assigned to each student behavior class, and the percentage of the total examination score represented by each student behavior class are shown in Table 4. Evidently, the principle emphasis in both Hour Examinations is on the student behavior of application.

The 14 questions on the Final Examination that deal with mechanics are all of the multiple-choice type. Nevertheless, six questions present quantitative problems requiring numerical solutions, and two other questions pose non-quantitative mechanics problems new to the

students. The relative emphasis on the several behaviors assessed by the mechanics questions on the Final Examination are shown in Table 4. Again, as for the two Hour Examinations, the principal emphasis is on application.

The measure of student achievement in mechanics is operationally defined in this study as the sum of a student's three scores on the First and Second Hour Examinations and on the mechanics questions of the Final Examination. Because two different forms were used for each of the Hour Examinations, the students' actual scores on all examinations were converted to standardized scores (mean = 500, S.D. = 100), and these were summed to obtain the criterion measure of Mechanics Achievement.

#### Methods of Analysis

Since one purpose of the present study is to find the relationship between identified input variables and students' success in learning classical mechanics, one necessary analysis is the determination of how the criterion measure of Mechanics Achievement just described is related to students' preinstructional knowledge, skills and status variables. The relationships of interest can be investigated in the type of study undertaken here, in which the experimental manipulation of conditions was neither desirable nor feasible, by analyzing correlations between variables and by a regression analysis on the criterion measure. From the observations of physics educators reported in the literature (see Introduction), it is apparent that three input

variables likely to enter into the prediction of the criterion measure, Mechanics Achievement, can be derived from the three instruments used in this study's preinstructional assessment, measuring, respectively, knowledge and preconceptions about motion, logical reasoning skills, and mathematical skills. Observations and opinions of certain physics educators also suggest that certain other characteristics of students might enter into the prediction of the criterion. Consequently, such variables as the amounts of high school science and mathematics studies, whether or not the student studied physics in high school, and the student's sex become candidates for consideration in the statistical analyses.

It should be recognized, however, that all the data collected in this study are not reducible to statistical treatment, nor were they intended to be. In particular, the Demonstration, Observation, and Explanation of Motion Test administered as a part of preinstructional assessment yielded an answer booklet for each student containing several hundred words of written responses to specific probing questions (see Appendix A), so that these answer booklets provide a valuable resource for constructing descriptions of the conceptions of motion held by the students. These conceptions could be constructed by considering the answer booklets to be protocol records and systematically applying techniques of verbal and logical analysis to these protocols. Results from the protocol analysis are reported in the following Findings section, and they serve to make understandable the statistical results which are reported first.



## Findings

### Predictions of Mechanics Achievement Score

The students' total scores for Mechanics Achievement, computed as described in the Procedures section, ranged from 849 to 2046, with a mean of 1499 and standard deviation of 248. Correlation coefficients between this criterion variable and nine input variables derived from the several diagnostic instruments and student status characteristics are presented in Table 6, which also shows the correlation between all pairs of input variables. The input variable "D.O.E. Test Correct Score" was constructed from the students' responses given to four key questions on the Demonstration, Observation, and Explanation of Motion Test. As indicated in the findings discussed in the next section, the four key questions on the D.O.E. Test encompass a significant aspect of a student's conceptualization of motion, so that the score derived from these questions is a reliable metric for this instrument. The input variable "Sex" was constructed as a dummy variable with male = 1 and female = 2. The numerical values for the other input variables are evident from their names and descriptions in the Procedures section.

As displayed in Table 5, the Mechanics Achievement Score is correlated significantly with only three input variables: D.O.E. Test Correct Score ( $p < .01$ ), Reasoning Score ( $p < .001$ ), Math Skills Score ( $p < .001$ ). Each of these three variables is significantly correlated with each of the other two and with the Sex variable. (Although Table 5 shows some additional statistically significant correlation

coefficients between input variables, these relationships are of no interest for the present analysis.) Examinations of cross-tabulation of the Mechanics Achievement Score versus each of the three significantly correlated input variables yielded the following further findings about the relationships:

(1) Students who obtained D.O.E. Test Correct Scores (5 or more) generally obtained scores above the mean on Mechanics Achievement (6 out of 7 scores), while students whose D.O.E. Test Correct Scores were low (2 or less) did not necessarily score below the mean on Mechanics Achievement (37 students of 64 did).

(2) Students who obtained high Reasoning Scores (7 or more) did not necessarily obtain scores above the mean on Mechanics Achievement (12 students of 18 did), while students whose Reasoning Scores were low (3 or less) tended to score below the mean on Mechanics Achievement (14 out of 18 students).

(3) Students who obtained high Mathematical Skills Scores (26 or more) tended to obtain scores above the mean on Mechanics Achievement (16 out of 21 cases), while students whose Math Skills Scores were low (13 or less) generally scored below the mean on Mechanics Achievement (12 out of 14 cases).

Using the four input variables with significant intercorrelations identified in Table 5, step-wise multiple regression analysis was carried out. The regression may be represented as:  $MA = DC + R + MS + SX$ , where MA = Mechanics Achievement Score, DC = D.O.E. Test Correct

Score, R = Reasoning Score, MS = Math Skills Score, and SX = Sex.

Table 6 gives the summary table for the multiple regression analysis and the computed regression equation. The multiple R of 0.572 is significant at the .01 level, and approximately 33% of the variance in Mechanics Achievement Score is explained by the four input variables. The contribution of the Sex variable is not significant, however, and almost the same percentage of variance in the criterion measure is explained by the variances in the D.O.E. Test Correct Score, Reasoning Score, and Mathematical Skills Score.

#### Protocol Analysis

The D.O.E. Test used in this study evolved from a demonstration-interview schedule developed for a previous study (Champagne & Klopfer, 1979) to probe elementary, middle, and high school students' understanding of the motion of physical objects. The use of demonstrations to define the problem space has two obvious advantages, namely: (1) the amount of verbal description necessary to set the parameters of the situation is reduced; and (2) the open ended questions yield copious data on which inferences about the students' conceptualization can be made. These features also proved advantageous for use with college students. A short answer test of the same basic ideas appropriate for college-age students would either be highly formal or excessively verbal. In either case, the short answer test would not be a good probe for the students' conceptions, either formal or informal, of the causality of motion, but an opportunity to assess both types of conceptions is provided by the D.O.E. Test. Four of the questions, namely A4, B1, C1, and D6, probed the students'

understanding of the equation central to classical mechanics,  $F = ma$ . Table 7 presents the particular relationships of the equation that the physical situation surrounding each question defined. Student answers to these four key questions were marked "correct" if the answer was consistent with the formal interpretation of the equation,  $F = ma$ . Credit was given for the answer even if it was based on faulty or partial information or on faulty logic.

The four key questions on the D.Q.E. Test provided a reliable measure of the students' pre-instructional knowledge of mechanics. It had been expected initially that the frequency of "correct" answers would be high and that more detailed information about the students' conceptualizations would be obtained from the protocol analysis. However, as the data in Table 8 indicate, the students demonstrated that they did not know the very basic relationships these key questions tested. These results were particularly surprising since about 70% of the students in the sample had studied high school physics, some for two years. A chi-square test showed that students in the sample who had studied high school physics did not score significantly better than those who had not. There are also significant sex differences in performance on these four key questions.

Analysis of "incorrect" answers to the key questions indicated that approximately one in five of the students in the sample believed that a dropped object reaches an instantaneous maximum velocity and then falls at constant speed. About four students in five believed that, all other things being equal, heavier objects fall faster than lighter ones, and about the same proportion of students believed that "lower (closer to

the earth) implies heavier." Perusal of student protocols provides ample evidence of the extent to which these beliefs are rationalized on the basis of various creative, idiosyncratic misconceptions about the relationships among force, weight (mass), and the motion of objects. The excerpts from student protocols in Tables 9 and 10 illustrate these various misconceptions which rationalize incorrect beliefs about the motion of objects.

Not only is the students' poor performance on the four key questions of the D.O.E. Test noteworthy; it is contrary to expectation. Pre-instructional knowledge of a subject-matter domain is usually a strong predictor of what is learned from instruction. However, the result from the intercorrelation analysis (Table 5) and cross-tabulations suggests that the D.O.E. Test may be tapping a different knowledge domain from the one tested by the mechanics items on the hour and final examinations of the course. The next step in the data analysis is based on the assumption that the propositional knowledge tapped by the preinstruction knowledge test is not inconsistent with what was taught in the course and tested for in the course's mechanics examinations. However, the preliminary analysis showed that the students who scored very well on the D.O.E. Test were not the same as those who scored well in Mechanics Achievement, a score derived from the hour and final examinations. Neither were those who scored low on the D.O.E. Test the same as those who scored low in Mechanics Achievement. To test the hypothesis that the students who score high on one or the other knowledge tests were somehow more similar than those who scored low on one or the other of the tests,

contrasting groups analyses of the D.O.E. Test protocols was carried out. Protocols of students who scored highest on the D.O.E. Test were contrasted with protocols of students who scored lowest on the D.O.E. Test and protocols of the highest scoring group in Mechanics Achievement were contrasted with protocols of those scoring lowest. The results of the two contrasting groups analyses are shown in Tables 11 and 12.

As a result of the contrasting groups analyses of the protocols, three dimensions along which the high and low scoring students differ were identified, namely: (1) the frequency of the use of technical terms; (2) the frequency with which students give evidence that they are reflective thinkers (that is, they think about their own thinking processes); (3) the frequency with which students report that their responses to questions are based on knowledge rather than on observation. These results suggest that, considering the three identified dimensions, there is more similarity among students who score well on either of the mechanics knowledge tests than between those who score well and those who score poorly.

## Discussion

The data analysis reported in the latter part of the Findings Section was guided by the working hypothesis that the D.O.E. Test and the Mechanics Achievement measure based on the Physics 10 course examinations were tapping into two separate knowledge structures. These knowledge structures can be characterized succinctly as (1) a formal system and (2) a belief system.

Our current conceptual model of these systems assumes that the formal system is abstract and can be applied to any situation involving motion in the macroscopic world. The propositional knowledge is represented formally and the mode of thought (procedural knowledge) in this system is formal.

The formal system stands in marked contrast to the belief system, which is informal and experience-based. The propositional knowledge in this system is bound to specific features of the physical world and, therefore, is not applicable to a variety of situations. For example, people functioning in this system use the proposition that "lower is heavier" to analyze the Atwood Machine and the proposition that "heavier falls faster" to analyze the time in free fall of the aluminum and lucite blocks. There is evidence in the protocols that in many instances propositional knowledge about these two situations is quite distinct. Individuals often come up with totally different misconceptions to explain their analysis of these two physical situations. The mode of thought characteristic of the belief system may be, but is not necessarily, informal. There is evidence in some



protocols that the mode of thought exhibited by a person using the belief system is formal. In most cases, however, there is not sufficient evidence to make any valid inferences about the mode of thought. Formal thought is always necessary for a person to function in the formal system, and it may or may not be exhibited by individuals functioning in the belief system.

There is probably considerable overlap in propositional knowledge in the two systems, especially for those individuals who have had some formal instruction in mechanics or who are in the process of learning the formal system. Some interesting (but sparse) data in the study suggest that the belief system has primacy and that certain features of a problem space may cue the belief system rather than the formal system. Three questions in the mechanics section of the final examination concern the Atwood Machine. The questions are reproduced in Table 13, and the proportion of students responding correctly to each question is noted. Question 12 is a multiple choice version of part C of the D.O.E. Test (see Appendix A). The formal analysis of question 12 is considerably simpler than the formal analysis of either question 13 or 14. Yet less than half as many students answered question 12 correctly. This observation suggests that the features of a problem cue students to function in the informal belief system. It should also be noted here that the manner of administering the D.O.E. Test may have been such as to cue the use of the informal system. By contrast, the formal system may have been cued by the mechanics examination questions, many of which involve applications of principles or generalizations (see Table 4), a process requiring formal reasoning.

The model we have postulated is consistent with the finding that the score on the Logical Reasoning Test is a predictor of success in classical mechanics as measured by the Mechanics Achievement Score (see Table 6). The protocol analysis provides another kind of information on logical reasoning skill that may have useful implications for instruction. In those instances where evidence of formal thought is found in the protocols, it is most often the case that the person either clearly distinguishes his or her observations from inferences or is in some other way reflective on his or her own thought processes. The student who has this capability will be much more aware of the function and value of a formal system for analyzing motion of objects. Further, the student who possesses this capability will be better able to distinguish between the formal and informal systems and will be less likely to revert to the informal system in instances where the problem space strongly cues the informal system.

The protocol of one student is unusual and interesting with regard to the hypothesized importance of reflective thinking in deriving maximum benefit from physics instruction. This student was among eight students in the lowest group on the D.O.E. Test Correct Response Scores (see Table 11); she answered none of the four key questions correctly. However, hers was the single highest total score on Mechanics Achievement; no student in the entire sample had a higher score. To D.O.E. Test question A5 ("On what did you base your answer to question 4--observation, knowledge about falling objects, or both?"); she answered:

"Observation, I don't really know any theories, tho' there is something in the back of my mind which says that an object falls at a constant

rate. I don't know if that's true or not.--- As I said above, I based it on the idea which may or may not be correct, that objects fall at a constant rate, if they don't have anything obstructing them, or don't pass through different mediums (like air vs. water).

This student's answer is wrong and is based on a misconception. However, because she is reflective about her own thought processes, we might predict on the basis of her protocol that the misconceptions will not be deliterious to her learning of the correct concept.

One instructional consequence of our hypothesized model of the formal and informal systems is that physics laboratory experiments and demonstrations should not be used in instruction either to verify theory or to induce principles. Rather, the laboratory experiments and demonstrations which are performed should be utilized primarily to demonstrate the contrasts between the results of an analysis of physical events which is based on common sense and one based on the tenets of the formal system of physics. The instructor should be constantly aware that the preinstructional status of most of the students finds them functioning in the informal system. During their instruction in mechanics, the students must make an important shift to the formal system if their achievement in mechanics is to meet the instructors' expectations of physics instructors indicated by the types of examination questions they generally emphasize. Consequently, the students need ample opportunities to contrast their informal interpretations of physical events with the formal interpretation required by the tenets of classical mechanics.

As shown in the preinstructional assessment, logical reasoning and mathematical skills are significantly correlated (see Table 5). Nevertheless, some comments should be made with respect to the effects

of general mathematics ability and specific mathematical skills on student achievement in mechanics. We hypothesize that the correlation between proficiency in specific mathematical skills prior to formal instruction with mechanics achievement can be explained, in part, by a simple analysis of the student's interactions with mechanics instruction, in this instance with the lectures.

The formal derivation and elaborations of the principles of mechanics is achieved by using mathematics as the medium of analysis and communication. Thus, for the student to understand the principles of mechanics, prior facility with the medium of communication is important. In those instances where the student either has little knowledge of the mathematics content or lacks facility in certain mathematical skills, we hypothesize that more of the student's attention will be focused on the mathematics (which is more familiar than the mechanics) than on the principles of mechanics. Assuming a finite attention capacity and competing demands of mathematics and physics, the student who is facile in the relevant mathematical skills clearly is at an advantage in attending to the physics content of a lecture. It is noteworthy that an informal tabulation and analysis of the questions asked by students in the physics lectures shows that half of the questions asked in lecture were about mathematics rather than physics. For example, in a problem on torque, a student asked how to use the fact that a certain angle in a right triangle is  $30^\circ$  to find the length of a side of the triangle.

An analysis of the questions that comprise the criterion measure of mechanics achievement indicates considerable overlap between the

skills tested for in the Mathematical Skills Test of the preinstructional assessment and the mathematics content of the mechanics examinations. However, this correspondence is probably not the critical one. The interactive effects of mathematical skills with classical mechanics is probably of primary significance in the students' comprehension of the lectures.

This analysis has implications for future research and for instructional practice. Microanalysis of the mathematics content of both the lectures and the textbook used in the course can provide a well-defined set of relevant mathematical skills and an indication of the relative frequency of their application during instruction. With such a set of basic mathematical skills in hand, it is possible to train students to a level of nearly automatic performance of the skills. The experimental demonstration that student achievement in mechanics is a function of the level of mathematical skills performance would provide empirical evidence to substantiate the proposed instructional effects hypothesis. Pending the availability of empirical evidence, it may even now be useful to emphasize that the ability to perform mathematical skills both accurately and quickly probably is very important for the successful learning of mechanics.

The more frequent use of technical vocabulary by students who score in the high groups in the preinstructional D.O.E. Test (see Table 11) and on Mechanics Achievement (see Table 12) deserves some further discussion. The finding serves as a reminder that propositional knowledge is important in the learning of even highly mathematical and formal subject matter, and it may provide some useful insight into the

difficulty students have in learning mechanics. Protocol analysis indicates that students who use technical vocabulary often use terms incorrectly, that is, when the criteria for correctness are the physicists' definitions for the terms. It is also the case that formal relationships among these technical terms often are defined incorrectly by the students. Even though the students' precision in using technical terms is poor, the frequency of use may be a significant factor in their learning and retention of classical mechanics. The propensity to use technically relevant vocabulary may be important in itself, or it is possible that a minimal knowledge of technical terms, even though the knowledge may be partial or imprecise, is crucial for comprehending the lectures and texts from which the students obtain their instruction.

It is important to note that many of the words that comprise the technical vocabulary of classical mechanics are words which are frequently used in natural language. Moreover, there is considerable overlap in the meanings of the words in the two contexts. Students frequently use a technical word with its natural language meaning in the context of formally analyzing the motion of an object. Overlaps in meaning are quite common for mechanics terms, and they may be a source of the difficulty students experience in learning classical mechanics.

### Conclusions

The data collected for this study provide empirical evidence for the assertion that students have difficulty learning classical mechanics. The fact that having high school physics had no discernible effect on the students preinstructional knowledge of mechanics or on their success in the course is noteworthy. It is also important to note that the mastery level in the course for mechanics was 51%. These data indicate that for a significant proportion of the student population in beginning physics, the instructional challenge is formidable. Finally, this study has sought to substantiate the assumption that fine-grained analysis of students' knowledge structures and of the interaction of features of these knowledge structures with instruction can provide valuable insights for the improvement of instruction.



Table 1

College Years and Majors of Students

<u>Year in College</u>			<u>College Major</u>		
First	25	(23%)	Biological Sciences	30	(27%)
			Physical Sciences	11	(10%)
Second	43	(39%)	Pre-Health Related Professions	39	(36%)
			*Usually not pre-med		
			Mathematics	3	( 3%)
Third	24	(22%)	Social and Behavioral Sci.	3	( 3%)
			Humanities	4	( 4%)
Fourth or more	4	( 4%)	Other	3	( 3%)
Unknown	14	(13%)	Unknown or undecided	17	(15%)
<hr/>			<hr/>		
	110			110	

Table 2

Number of Years of High School Science and Mathematics  
Studied by Students

<u>Years of H.S. Science</u>			<u>Years of H.S. Mathematics</u>		
1	1	( 1%)	1	1	( 1%)
2	6	( 6%)	2	5	( 5%)
3	15	(14%)	3	14	(13%)
4 or more	82	(75%)	4 or more	83	(76%)
Unknown	6	( 5%)	Unknown	6	( 5%)
	<hr/>			<hr/>	
	110			110	

### Credits in College Science and Mathematics Previously Earned by Students

110:

Table 4

Student Behaviors With Respect to Mechanics  
Assessed on the Hour and Final Examinations

STUDENT BEHAVIORS	FIRST HOUR EXAMINATION		SECOND HOUR EXAMINATION		FINAL EXAMINATION	
	<u>Points</u>	<u>Pct.</u>	<u>Points</u>	<u>Pct.</u>	<u>Points</u>	<u>Pct.</u>
(A.3) Knowledge of concepts	11	20%	2	7%	1	7%
(A.4) Knowledge of conventions	3	5%				
(A.8) Knowledge of principles and laws			4	13%	1	7%
(A.10) Identification of concepts or principles in a new context	8	15%	4	13%	2	14%
(A.11) Translation of concepts or principles to another symbolic form			4	13%	2	14%
(F.1) Application of knowledge and methods to a new problem	33	60%	16	53%	8	57%
	—		—		—	
Total	55		30		14	

Table 5

## Intercorrelation Matrix for Mechanics Achievement Score and Input Variables

Variable Number and Name	1	2	3	4	5	6	7	8	9	10
1. Mechanics Achievement Score	1.00	0.24**	0.38***	0.53***	-0.08	0.09	0.09	0.09	0.14	0.13
2. D.O.E. Test Correct Score		1.00	0.35***	0.23*	-0.33***	0.08	0.05	-0.03	0.03	0.09
3. Reasoning Score			1.00	0.32***	-0.22*	-0.04	0.02	-0.05	-0.07	0.07
4. Math Skills Score				1.00	-0.07	0.13	0.15	0.31***	-0.04	-0.26**
5. Sex					1.00	-0.02	0.08	0.03	-0.05	-0.07
6. Years H.S. Physics						1.00	0.30***	0.33***	-0.05	0.02
7. Years H.S. Science							1.00	0.44***	0.18*	-0.18*
8. Years H.S. Math								1.00	0.06	0.10
9. Credits College Science									1.00	0.15
10. Credits College Math										1.00

\* p &lt; .05

\*\* p &lt; .01

\*\*\* p &lt; .001

Table 6

Multiple Regression Summary Table  
for Prediction of Mechanics Achievement Score  
of Introductory College Physics Students

Variable Number and Name	Multiple R	R Square	% of Variance Explained
2. D.O.E. Test Correct Score	0.237	0.056	5.6%
3. Reasoning Score	0.378	0.143	8.7%
4. Math Skills Score	0.570	0.325	18.3%
6. Sex	0.572	0.327	0.2%

$$MA = 920.9 + 11.9DC + 33.7R + 17.2MS + 22.7SX$$

Table 7

Relationships Tested by Four Key Questions  
on the Demonstration, Observation, and Explanation of Motion Test

<u>Question Number and Text</u>	<u>F = ma Relationship Tested</u>
A4. When the eraser falls from the red mark to the floor, how does its speed as it passes the blue mark compare with its speed as it passes the green mark?	<p>Bodies in free fall are constantly accelerated.</p> $g = \frac{F}{m}$ <p>where <math>g</math> = acceleration due to gravity  <math>F \approx</math> force of gravity on the object  <math>m</math> = mass of the object</p>
B1. How does the time it takes for the aluminum block to fall from the red mark to the floor compare with the time it takes for the lucite block to fall from the red mark to the floor?	<p>Two objects of the same shape and volume but of different mass have the same acceleration in free fall.  <math>(g \text{ is a constant})</math></p>
C1. How does the weight of the bucket compare with the weight of the block?	<p>For an unaccelerated system, the net force acting on the system is zero.</p> $(\text{when } \vec{a} = 0, \Sigma \vec{F} = 0)$
D6. How does the bucket's speed at the blue mark compare with its speed at the green mark?	



Table 8  
Proportions of Correct and Incorrect Responses to Four  
Key Questions on the Demonstration, Observation, and  
Explanation Test by Students Who Did and Did Not  
Study High School Physics

(N = 105)

	Proportion of Correct Responses	Proportion of Incorrect Responses	Studied H.S. Physics vs. No H.S. Physics
<u>Question A4.</u> (text given below)			
Students Who Studied High School Physics (73)	.82	.18	$\chi^2 = 0.54$ $p > .40$
Students With No High School Physics (32)	.75	.25	
All Students (105)	.80	.20	
<u>Question B1.</u>			
Studied H.S. Physics	.31	.69	$\chi^2 = 0.83$ $p > .30$
No H.S. Physics	.23	.77	
All Students	.28	.72	
<u>Question C1.</u>			
Studied H.S. Physics	.08	.92	$\chi^2 = 1.19$ $p > .20$
No H.S. Physics	.16	.84	
All Students	.11	.89	
<u>Question D6.</u>			
Studied H.S. Physics	.71	.29	$\chi^2 = 0.38$ $p > .50$
No H.S. Physics	.66	.34	
All Students	.70	.30	

Question Texts:

- A4. When the eraser falls from the red mark to the floor, how does its speed as it passes the blue mark compare with its speed as it passes the green mark?
- B1. How does the time it takes for the aluminum block to fall from the red mark to the floor compare with the time it takes for the lucite block to fall from the red mark to the floor?
- C1. How does the weight of the bucket compare with the weight of the block?
- D6. How does the bucket's speed at the blue mark compare with its speed at the green mark?

Table 9

Misconceptions Excerpted from Student Protocols  
for the D.O.E. Test to Rationalize Their Beliefs  
about the Velocity of Objects in Free Fall

Belief A: The velocity of objects in free fall is constant.  
(A belief held by students giving "incorrect" answers  
to question A4)

Misconceptions: (from question A6)

- (S#306) My answer is based on a theory which states that gravity pulling on the eraser will have a steady force applied to it until it lands on another steady state causing it to fall at the same velocity. I'm not sure what exact theory it is, if it is one at all
- (S#421) How fast it drops is determined by the eraser's mass- which remains constant at all levels.
- (S#308) The maximum speed attainable via gravity is 32 ft/sec
- (S#417) Gravitational pull is the same for each mark.
- (S#440) Gravity pulls down the object at the same speed. No matter where the object would fall from the speed at any given point would be the same.
- (S#301) Falling objects can reach only a certain velocity when the force moving them is gravity.
- (S#335) The eraser falls at a constant rate, i.e. the rate is equal when it passes the blue and green. The mass of the eraser is constant, the force of gravity is also constant. Initial rate is zero.
- (S#436) Gravitational forces are independent of relative masses.
- (S#402) The force of gravity is constant 32 ft/sec. Therefore if it is constant, the speed of the falling object remains constant. The speed and movement of the falling objects is due to gravity. How fast it drops is determined by the eraser's mass - which remains constant at all levels.

Belief B: Heavier (freely falling) objects fall faster than lighter objects. (A belief held by students giving "incorrect" answers to question B1.)

Misconceptions: (from question B3)

- (S#318) Although the blocks are of equal size it is doubtful that they are of equal density and weight. Gravity being constant, then velocity must be partly dependent on weight and density. Therefore if aluminum is more dense and heavier than lucite, then it will fall faster.
- (S#419) Same sized pieces of things have different "weights" - that is gravity pulls things according to their molecular weights.
- (S#442) The heavier or more dense object, the greater the amount of pull or attraction gravity has on it. The aluminum block was heavier than the lucite block and so gravity had a greater pull on it so it fell faster.
- (S#460) The heavier an object the faster it falls. Since lucite is denser than aluminum, it falls faster.
- (S#304) The aluminum is heavier and falls to earth faster due to more force.
- (S#418) (No observation) I would say, however, that the heavier object should hit the ground first. Again, objects falling outside a vacuum are subject to air currents etc. Therefore the speed of each object is related to its weight.
- (S#433) Aluminum could be a denser substance than lucite, therefore making it fall faster, gravity has greater effect on it.
- (S#463) a = fm The acceleration or speed of an object is dependent on the mass of the object and the gravitational force.
- (S#312) The greater the density, the greater the effect gravity has on it. What falls faster a feather or a safe.
- (S#403) The heavier the object the faster the pull of gravity.

Table 10

Misconceptions Excerpted from Student Protocols for the D.O.E. Test to Rationalize Their Beliefs about the Weight of Objects Suspended on the Atwood Machine.

**Belief:** The object (block of wood) which hangs lower on the Atwood Machine is heavier than the object (bucket of sand) which hangs higher. (A belief held by some students giving "incorrect" answers to questions C1)

Misconceptions: (from question C3)

- (S#323) The block of wood must weigh more since it pulled the bucket of sand upward. The block is much more compact and bigger than the styrofoam container containing the sand.
- (S#345) For equal, they would be equal distance from pulley but block is lower. Same principle as seesaw.
- (S#354) If the weight exerted on both was the same, they would parallel each other. Gravity has greater affect on the block because of its mass.
- (S#320) The block is denser than the sand and thereby using the pulley as a lever can lift the sand with ease.
- (S#401) The weight of objects can be compared by somehow comparing the length of the string of each of the objects when balanced over the pulley.
- (S#425) The pulley was set up somewhat like a scale. The heavier object is closer to the ground, indicating that it is heavier.
- (S#427) A heavy object can be placed farther from the pulley to work out a balance, while the lighter object must be farther from the ground (force of gravity).
- (S#309) In order for something to balance, a center of gravity must be reached. To obtain this new center heavier objects must move further away from the original center and lighter objects must move closer.
- (S#315) The greater weight on the pulley system will be nearer the ground as an equilibrium between the different weights is established.
- (S#410) Weight takes into account the force of gravity. Since both objects are affected by the earth's gravity, (and on the same support), comparatively the bucket weighs less.
- (S#419) Gravity pulls these two objects against one another. Net pull on the block is more.
- (S#442) Because the bucket is lighter, it is able to rest at a higher position of equilibrium, the weight of the block brought it to this position.
- (S#428) Because the block is heavier it created an unbalanced force pulling harder downward than the bucket whose downward force is less, being lighter in weight.

Table 11

Comparisons of High and Low Correct Response Groups  
on Various Criteria

Criterion	High Correct Response Group (N = 7)	Low Correct Response Group (N = 8)
Total Number of Words Used in Answer Booklet for D.O.E. Test		
Range	227 - 399	133 - 562
Group mean	272	270
Frequency of Use of Technical Terms in All Responses on D.O.E. Test		
Terms: gravity	28	11
force	13	10
acceleration	13	0
velocity	4	0
equilibrium	3	0
balance	2	1
friction	2	0
Total	65	22
Mean per student	9.3	2.8
Frequency of Reports of Knowledge or Observation Basis for Responses to Four Key Questions on D.O.E. Test		
Knowledge basis only	14*	1
Knowledge and observation	8	10
Observation basis only	6	15
Not codable	0	6
* All males		
Number of Students Whose Responses on D.O.E. Test Display Evidence of Logical Reasoning		
Logical reasoning	2	1
Illogical reasoning	0	4
No evidence of reasoning	3	2
Not codable	2	1
Number of Students Who Did or Did Not Study High School Physics		
Studied h.s. physics	5	4
No h.s. physics	2	4
Total Score for Mechanics Achievement (2 hour exams plus final)		
Range	1423 - 1910	1222 - 2046
Group mean	1711	1470
Standard deviation	165	260
Point biserial correlation - group with score = 0.26		

Table 12

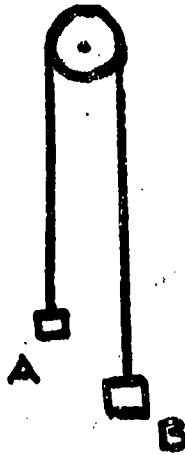
Comparison of High and Low Mechanics Achievement  
Score Groups on Various Criteria

Criterion	High Mechanics Achievement Score Group (N = 10)	Low Mechanics Achievement Score Group (N = 10)
Total Number of Words Used in Answer Booklet for D.O.E. Test		
Range	164-562	180-385
Group mean	247	243
Frequency of Use of Technical Terms in All Responses on D.O.E. Test		
Terms: gravity	21	17
force	17	11
acceleration	13	2
velocity	3	2
equilibrium	0	0
balance	0	0
friction	0	0
Total	54	32
Mean per student	5.4	3.2
Frequency of Reports of Knowledge or Observation Basis for Responses to Four Key Questions on D.O.E. Test		
Knowledge basis only	10 (all male)	1
Knowledge and observation	16	23
Observation basis only	14	16
Not codable	0	0
Number of Students Whose Responses on D.O.E. Test Display Evidence of Logical Reasoning		
Logical reasoning	4	0
Illogical reasoning	1	0
No evidence of reasoning	5	10
Not codable	0	0
Number of Students Who Did or Did Not Study High School Physics		
Studied h.s. physics	8	7
No h.s. physics	2	3

Table 13

Three Questions Concerning the Atwood Machine  
from the Physics 10 Course Final Examination

The figure at the right is to be used for Questions 12, 13, and 14. A and B are two masses. They are connected by a very long massless string which passes over the pulley. There is a small amount of friction in the pulley. The pulley has a small mass.



Proportion of Students  
Answering Question Correctly

12. If the masses in the figure remain at rest, what can be said of them?
- a) B's mass is a little bit greater than A's mass.
  - b) A's mass is a little bit greater than B's mass.
  - c) A and B have nearly the same mass but one cannot say which is greater.
  - d) Nothing at all can be said about their masses.

0.33

13. If B is descending at a constant velocity, what can be said of the masses?
- a) B's mass is a little bit greater than A's mass.
  - b) A's mass is a little bit greater than B's mass.
  - c) A and B have nearly the same mass but one cannot say which is greater.
  - d) Nothing at all can be said about their masses.

0.72

14. If B is descending at a constant velocity, we can expect that
- a) it will keep on descending at constant velocity until it hits the floor or A hits the pulley.
  - b) It will slow down and gradually come to a stop unless it first hits the floor or A hits the pulley.
  - c) it will speed up until it hits the floor or A hits the pulley.
  - d) Nothing can be said without more specific information.

0.69

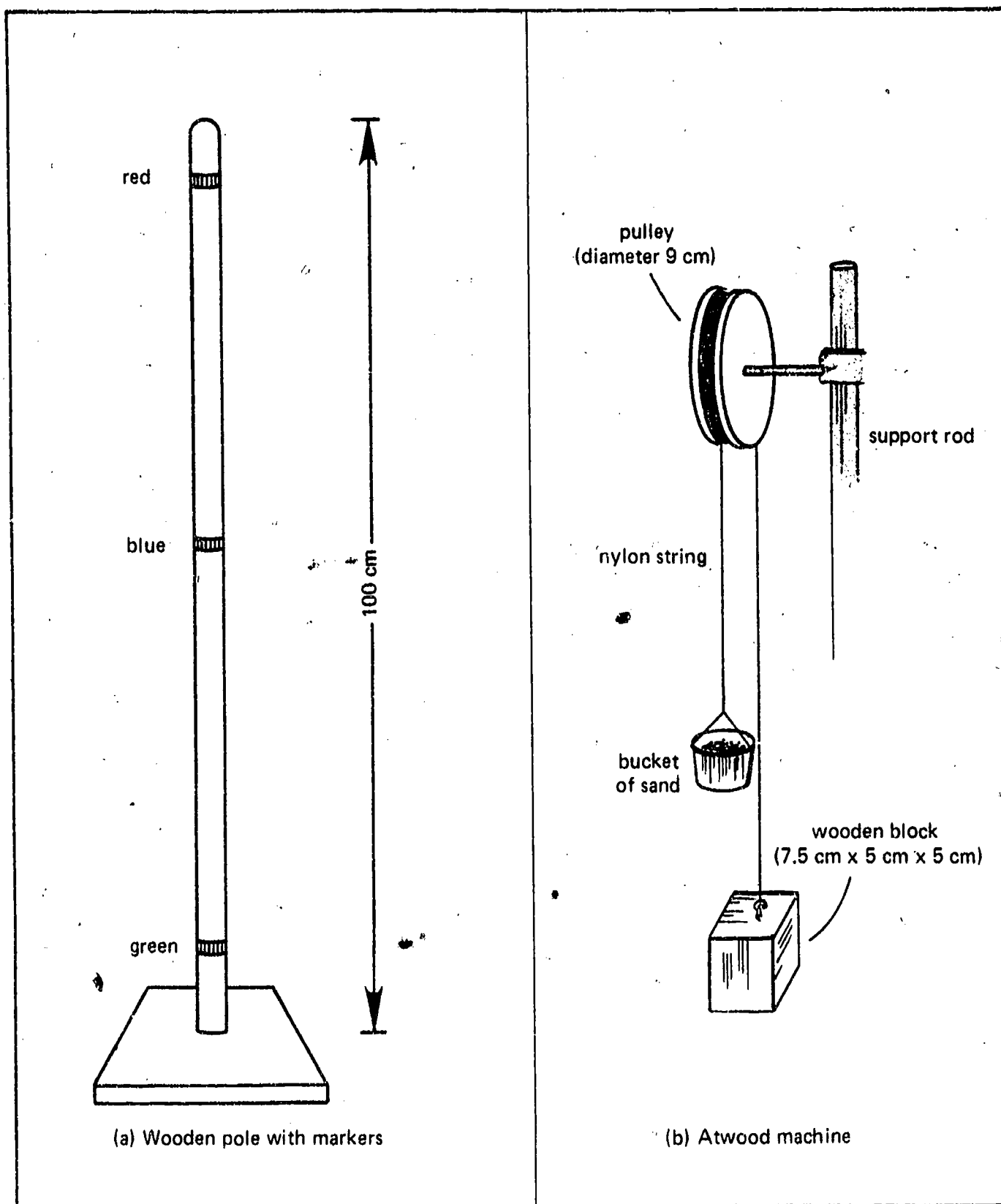


Figure 1. Apparatus used in the Demonstration, Observation, and Explanation of Motion Test.



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## Appendix A

### Questions in Answer Booklet of the Demonstration, Observation, and Explanation of Motion Test.

Listed below are the questions included in the answer booklet for the Demonstration, Observation, and Explanation of Motion Test which was used as a preinstructional measure of students' interpretation of the motion of objects in the present study. This listing contains additional identifying information about the several test sections and parts that does not appear in the actual answer booklet. The spaces where students write responses between questions in the answer booklet also have been eliminated.

#### Section A - Free Fall (one object)

##### Questions

- A. 1. What did you observe?
- A. 2. What sets the eraser in motion?
- A. 3. Why does the eraser not start moving when the pad is under it?
- A. 4. When the eraser falls from the red mark to the floor, how does its speed as it passes the blue mark compare with its speed as it passes the green mark?
- A. 5. On what did you base your answer to question 4--observation, knowledge about falling objects, or both?
- A. 6. If you based your answer to question 4 on some knowledge, explain which information, theories, or generalizations you used to arrive at your answer.

Section B - Free Fall  
(two objects of the same size but different  
mass; released simultaneously)

Questions

- B. 1. How does the time it takes for the aluminum block to fall from the red mark to the floor compare with the time it takes for the lucite block to fall from the red mark to the floor?
- B. 2. On what did you base your answer to question 1--observation, knowledge about falling objects, or both?
- B. 3. If you based your answer to question 1 on some knowledge, explain which information, theories, or generalizations you used to arrive at your answer.

Section C - Atwood Machine  
(different objects of the same mass; system static)

Questions

- C. 1. How does the weight of the bucket compare with the weight of the block?
- C. 2. On what did you base your answer to question 1--observation, knowledge about falling objects, or both?
- C. 3. If you based your answer to question 1 on some knowledge, explain which information, theories, or generalizations you used to arrive at your answer.

Section D - Atwood Machine  
(different masses; system in motion)

Part D. I. - Grains of Sand.

Questions

- D. 1. Prediction-
- D. 2. On what basis did you make your prediction?
- D. 3. Observation - (15 grains of sand)

Part D. II. - Scoop of Sand.

Questions

- D. 4. When a full scoop of sand was added to the bucket, was the bucket's motion different from its motion when 15 grains of sand were added? If so, describe the differences you observed.
- D. 5. How do you explain any difference you observed?

Part D. III. - Speed.

Questions

- D. 6. How does the bucket's speed at the blue mark compare with its speed at the green mark?
- D. 7. On what did you base your answer to question 6--observation, knowledge about falling objects, or both?
- D. 8. If you based your answer to question 6 on some knowledge, explain which information, theories, or generalizations you used to arrive at your answer.

Part D. IV. - Two Scoops of Sand

Questions

- D. 9. How does the bucket's speed at the blue mark with 2 extra scoops of sand compare with its speed at the blue mark with 1 extra scoop of sand?
- D. 10. Make up a rule which states how adding sand affects the rate of fall of the bucket.

Section E - Atwood Machine  
(different objects of equal mass;  
system in motion at constant speed)

Questions

E. 1. How does the weight of the bucket compare with the weight of the block?

E. 2. There are two forces acting on the bucket: the downward force due to gravity and the upward force due to the string. Is the downward force due to gravity

- (a) equal to
- (b) greater than
- (c) smaller than

the upward force of the string?

My answer is \_\_\_\_\_

E. 3. There are two forces acting also on the block: the downward force due to gravity and the upward force due to the string. Is the downward force due to gravity

- (a) equal to
- (b) greater than
- (c) smaller than

the upward force due to the string?

My answer is \_\_\_\_\_

E. 4. Is the force of the string on the block

- (a) equal to
- (b) greater than
- (c) smaller than

the force of the string on the bucket?

My answer is \_\_\_\_\_

E. 5. Is the force of the gravity on the block

- (a) equal to
- (b) greater than
- (c) smaller than

the force of gravity on the bucket?

My answer is \_\_\_\_\_

Section F - Atwood Machine  
(with cylinders of equal mass;  
system in motion at constant speed)

Questions

- F. 1. Why does the cylinder move down?
- F. 2. Why does the cylinder continue in motion after the push stops?

Section G - Atwood Machine  
(transfer of string and cylinders)

Questions

- G. 1. Prediction
- G. 2. What are the reasons for your prediction?
- G. 3. If your prediction was incorrect, go to question 3a.  
If your prediction was correct, go to question 3b.
- 3a. What reasons can you give now to explain your observation?
- 3b. Do you want to add any comment about your observation?